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The effect of aluminum substitution on the magnetic properties of iron-boron-silicon amorphous alloy

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Abstract The specific magnetization of as-quenched amorphous ribbon of compositions $Fe_{82}Si_8B_{10}$ and $Fe_{82}Al_3Si_5B_{10}$ have been measured at room temperature using Vibrating Sample Magnetometer (VSM) The latter composition was formed by replacing three out of the eight silicon atoms by Al atom per formula unit Initial permeability (μ_i), frequency dependence of the complex permeability $\mu_i(f)$ and relative quality factor ($\mu_i / \tan\delta$) have been measured in the frequency range 1 KHz to 13 MHz The measurements have been carried out for the as-quenched and annealed conditions using LCR bridge It is observed that due to aluminum substitution magnetization increases while initial permeability and relative quality factor decreases in the low field region Initial permeability increases with increasing annealing temperature of the ribbons upto a certain value and then decreases for both the compositions

Keywords Amorphous ribbons, magnetic properties, initial permeability

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1. Introduction

Amorphous magnetic alloys are of great interest as a soft magnetic material for their static as well as dynamic applications. The amorphous transition metal-metalloid (TM-M) alloys with TM = Fe, Co, Ni and M = B, P, C, Al or Si have recently received much attention for their potential technological and commercial applications such as power supplies, transformers, magnetic heads and magnetic shielding. The dynamic measurements of the amorphous magnetic ribbons $Fe_{82}Si_8B_{10}$ and $Fe_{82}Al_3Si_5B_{10}$ have been done to determine the effect of aluminum substitution in Fe-Si-B ribbon. The dependence of the complex permeability and relative quality factor on frequency and annealing temperature have been measured at room temperature for both the samples. The field dependence of magnetization for the samples have been measured and the saturation magnetization as affected by the substitution of Al for Si has been determined.

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The low field behavior corresponds to the reversible initial permeability arising from 180° domain wall movements. The theoretical models have been proposed for describing the motion of 180° Bloch wall as described by Polivanov [1], Pry and Bean [2], Bishop [3] and Ban *et al* [4]. The measurement of complex permeability gives us valuable information about the domain wall movements. The real and imaginary components of the complex permeability in ac or dynamic condition have been measured as a function of the instantaneous value of a sine wave core current density by means of an adapted ac bridge method described by Buttino *et al* [5]. Actually, under ac condition, the number of domain walls increases and more deeply pinned walls begin to move with increasing frequency as reported by Washko *et al* [6]. The thermal treatment alters the magnetic properties of amorphous ribbons. The magnetic properties as a function of frequency have been analyzed by complex permeability formalism which has led to the resolution of several magnetization mechanisms [7-9].

2. Experimental

Both the iron-aluminum-silicon-boron and iron-silicon-boron amorphous ribbons samples have been prepared by rapid quenching method using the single roller technique [10-12]. The molted alloy is then subjected to a cooling rate of about 10^6 °C/s to secure the amorphous state. The ribbons are of about 6 mm width and 20-25 μm thick. The amorphous nature of the ribbons were confirmed by X-ray diffraction using Cu-Kα radiation.

The amorphous ferromagnetic ribbons were wound in a toriodal shape cores having as outer diameter 13-15 mm and inner diameter 10 mm. The measurements were performed at room temperature using an ac field with a very low constant value of H = 0.11 A/m and a frequency ranging from 1 KHz to 13 MHz. The toriodal ring shaped specimens were chosen so that no free poles are developed and demagnetizing field is zero. The measurements have been carried out for both the samples in the as-quenched condition and also after annealing. In order to study the influence of annealing, both the samples were annealed at temperatures from 100°C to 500°C with an interval of about 100°C. The highest annealing temperature was ~ 500°C which is higher than the curie temperature T_c and the crystallization temperature T_x.

The frequency dependence of the complex permeability and the core loss were measured by means of an impedance analyzer (LCR bridge) using an adapted ac bridge method [5] upto the MHz range. The bridge was operated with an audio frequency test field H of amplitude at least ten times lower than the coercivity of the samples. The initial permeability μ_i of the amorphous ribbons which is extrapolated to zero frequency and for vanishing magnetic field is calculated. Relative quality factors (μ_i / tan δ) were determined. Analogous results have been found for the loss factor from direct value of tan $\delta = (\mu'' / \mu')$ of the impedance analyzer.

3. Results and discussion

The dynamic magnetic properties of as-quenched and annealed amorphous magnetic ribbons with composition $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ have been determined. The dynamic measurements of these amorphous alloys have been carried out to determine the frequency dependence of the complex permeability $\mu = \mu' - i\mu''$, loss factor (tan δ) and relative quality factor (μ_i / tan δ). The effect of aluminum substitution on the complex permeability, relative quality factor, magnetization in Fe-B-Si amorphous ribbons is explained on the basis of the existing theories.

The initial permeability (μ_i) of the amorphous magnetic ribbons which is extrapolated to zero frequency and for vanishing magnetic field is estimated for both the compositions. Since the permeability can not be measured without applying some field, the initial permeability μ_i of the amorphous ribbons at very low frequency in our dynamic or ac measurement, is assumed as a limiting case that corresponds to a static field.

Initial permeability is controlled by the irreversible part of the domain motion and the preparation technique determines the defects and the associated energy barriers to domain wall motion. Another accurate way to determine the initial permeability μ_i is from the plot of the imaginary part of complex permeability (μ'') against the real part of the complex permeability (μ'). For any applied field, this representation shows a semi-circle for the high frequency range. For low frequencies, when the applied field is lower than or equal to the propagation field, a short, vertical spike is observed [13]. The value of the initial permeability μ_i is determined from the semi circle's diameter *i.e.* from the inter-section of the semi-circle with μ' axis. In the Figure 1 and Figure 2, the results for the as quenched sample with composition $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ are given. The calculated parameter of both the samples are shown in Table 1.

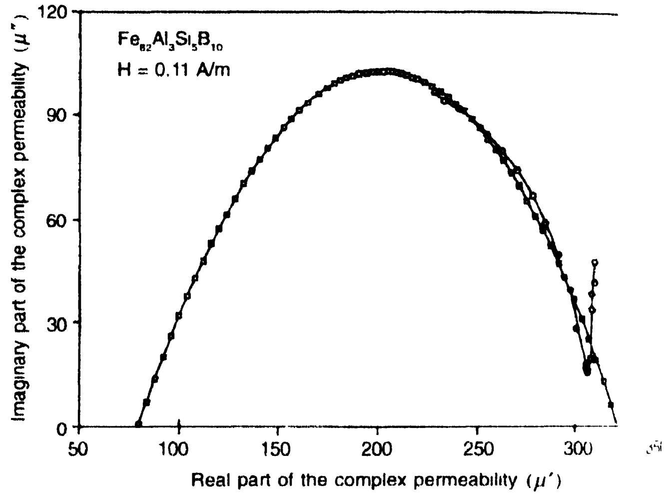

Figure 1. Imaginary part of complex permeability (μ'') as a function of the real part of complex permeability (μ') of as quenched amorphous magnetic ribbon with composition $Fe_{82}Al_3Si_5B_{10}$ at H = 0.11 A/m □- Fitted curve and o– Experimental curve

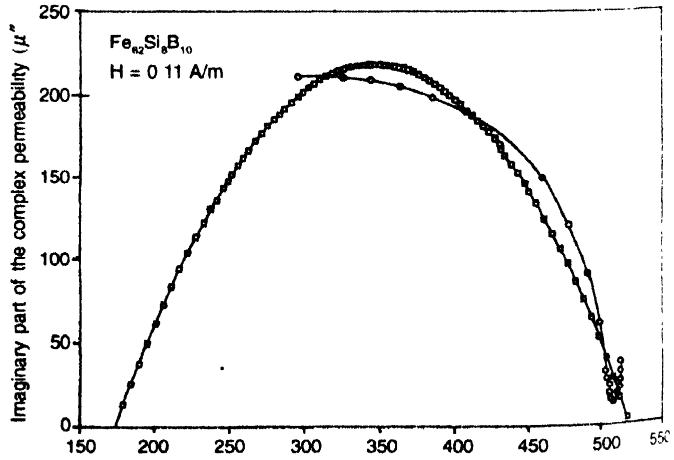

Figure 2. Imaginary part of complex permeability (μ'') as a function of the real part of complex permeability (μ') of as quenched amorphous magnetic ribbon with composition $Fe_{82}Si_8B_{10}$ at H = 0.11 A/m □- Fitted curve and o–Experimental curve.

Table 1. Initial permeability and saturation magnetization for both the compositions in the as-quenched condition.

Samples	Initial permeability (μ_i)	Saturation magnetization (σ_s) (emu/gm)
$Fe_{82}Al_3Si_5B_{10}$	329	184.5
$Fe_{82}Si_8B_{10}$	529	159

The frequency dependence of the real part of the complex permeability of as-quenched and annealed samples are shown in Figure 3 and Figure 4 for composition $Fe_{82}Si_8B_{10}$ and $Fe_{82}Al_3Si_5B_{10}$ respectively. The amorphous ribbon with composition $Fe_{82}Si_8B_{10}$ shows that permeability decreases as frequency increases in the low frequency range and remains constant over a wide range of frequency (10 KHz to 1 MHz). The permeability of the aluminum substituted sample *i.e.* $Fe_{82}Al_3Si_5B_{10}$ decreases as the frequency increases in the low frequency range which is the same as occured in sample without aluminum *i.e.* $Fe_{82}Si_8B_{10}$. But the permeability here is nonsteady upto the frequency of 100 KHz and then become stable between the frequency range 100 KHz to 3 MHz. This indicates that the amorphous ribbon without aluminum is more suitable than the ribbon with aluminum in the low frequency region. But in the high frequency region, Al substituted ribbon in more suitable as core material since the permeability here is stable upto 3 MHz. The initial permeability as a function of frequency at room temperature in low field *i.e.* H = 0.11 A/m is plotted in Figure 5 for both the specimens. The as-quenched specimen shows a sharp decrease in permeability above 1 MHz for composition $Fe_{82}Si_8B_{10}$ and 3 MHz for composition $Fe_{82}Al_3Si_5B_{10}$. The annealed specimens have similar frequency dependence, although the permeabilities are different depending on the annealing temperature as shown in Figure 3 and 4. It is observed here that due to annealing the quality of the ribbon with composition $Fe_{82}Si_8B_{10}$ increases for annealing temperature upto 350°C. In the case of the sample $Fe_{82}Al_3Si_5B_{10}$ the corresponding annealing temperature is 400°C.

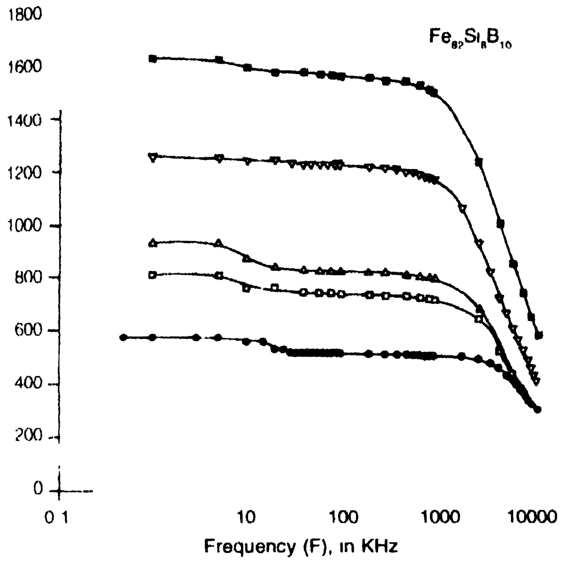

Figure 3. Frequency dependence of the real part of complex permeability of amorphous ribbons with composition $Fe_{82}Si_8B_{10}$ for different annealing temperatures ●- 25°C, □- 150°C, Δ- 225°C, V- 300°C, ■- 350°C, o- 400°C and ▲ 450°C

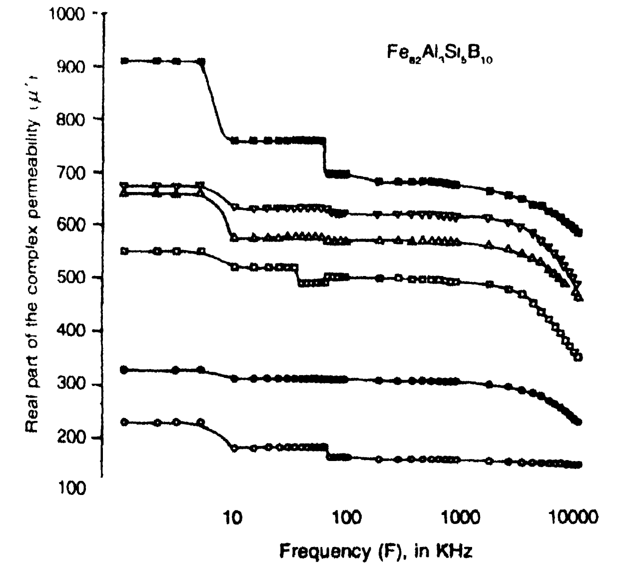

Figure 4. Frequency dependence of the real part of complex permeability of amorphous ribbons with composition $Fe_{82}Al_3Si_5B_{10}$ for different annealing temperatures. □- 100°C, Δ- 200°C, ∇- 300°C, ●- 25°C, ■- 400°C and o- 500°C

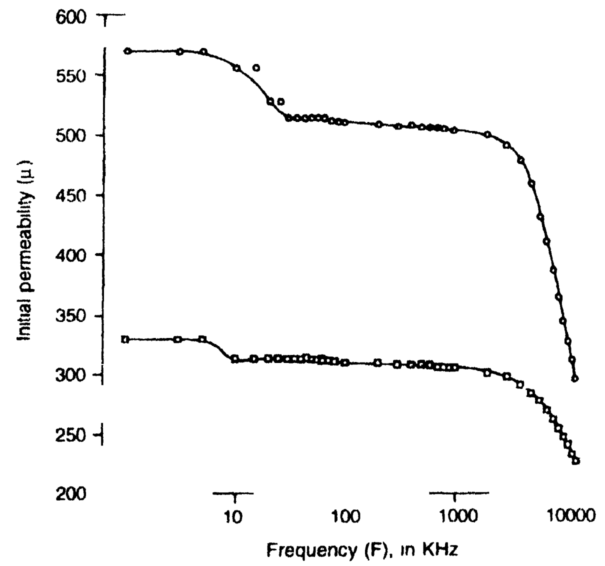

Figure 5. Initial permeability as a function of frequency at room temperature in a low field of H = 0.11 A/m of amorphous ribbons with compositions $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$. □- $Fe_{82}Al_3Si_5B_{10}$ and o- $Fe_{82}Si_8B_{10}$

Under ac or dynamic condition, the number of domain walls increases and with the increase of frequency more deeply pinned walls begin to move [6]. Moreover, when the magnetizing field varies, the stabilization of the domain walls in very deep potential walls is prevented and some walls are continuously kept free from their pinning centers. All these effects contribute to an increase of the real part of the complex permeability, but at the same time the imaginary component is also influenced, particularly due to eddy current effects. The values of the initial permeabilities corresponding to various annealing temperatures are plotted in Figure 6 for both the samples. These increase in μ_i suggest that a number of walls are nucleated and that they are free to sweep through the sample by freeing themselves from the pinning sites.

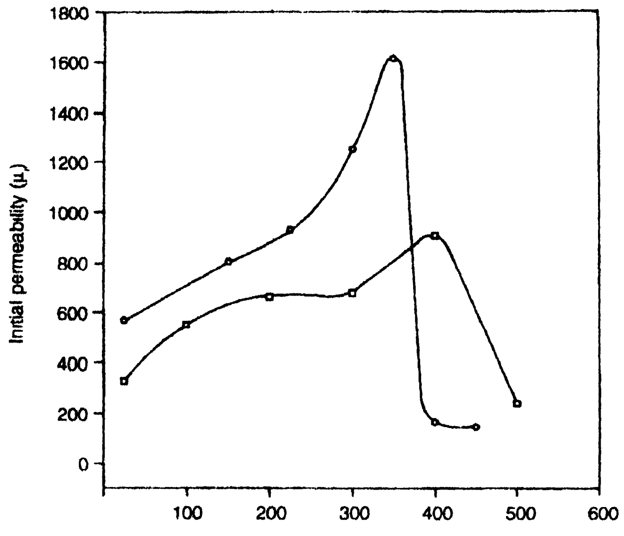

Figure 6. Annealing temperature dependence of the initial permeability of amorphous magnetic ribbons with compositions $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ □- $Fe_{82}Al_3Si_5B_{10}$ and o- $Fe_{82}Si_8B_{10}$.

It is observed that the permeability of Fe-B-Si ribbon decreases with aluminum substitution indicating that $Fe_{82}Al_3Si_5B_{10}$ is less suitable as core material rather than $Fe_{82}Si_8B_{10}$. From Figure 6, it is observed that for sample $Fe_{82}Si_8B_{10}$ initial permeability increases with annealing temperature upto 350°C and then decrease with the further increase of the annealing temperature. For the sample $Fe_{82}Al_3Si_5B_{10}$, permeability increases for annealing temperature upto 400°C and then decreases with further increase of annealing temperature. The increase of permeability with the annealing temperature is explained as due to the reduction of energy barriers which control the reversible domain wall movements. From the dependence of permeability on annealing temperature, the Curie temperature T_c have been estimated as 350°C for the $Fe_{82}Si_8B_{10}$ glass and 400°C for the $Fe_{82}Al_3Si_5B_{10}$ glass (Figure 6). This shows that it is not safe to use the ribbons at temperatures above 350°C for $Fe_{82}Si_8B_{10}$ and 400°C for $Fe_{82}Al_3Si_5B_{10}$.

The relative quality factor (μ_i / tan δ) of the amorphous magnetic ribbon $Fe_{82}Si_8B_{10}$ has very high value in the frequency range 100 KHz to 3 MHz having low loss factor. The ribbon $Fe_{82}Al_3Si_5B_{10}$ has a low value of the relative quality factor and high loss factor in comparison with $Fe_{82}Si_8B_{10}$ as shown in Figure 7. High relative quality factor and low loss factor indicate that the sample without aluminum can be very useful as a soft magnetic material.

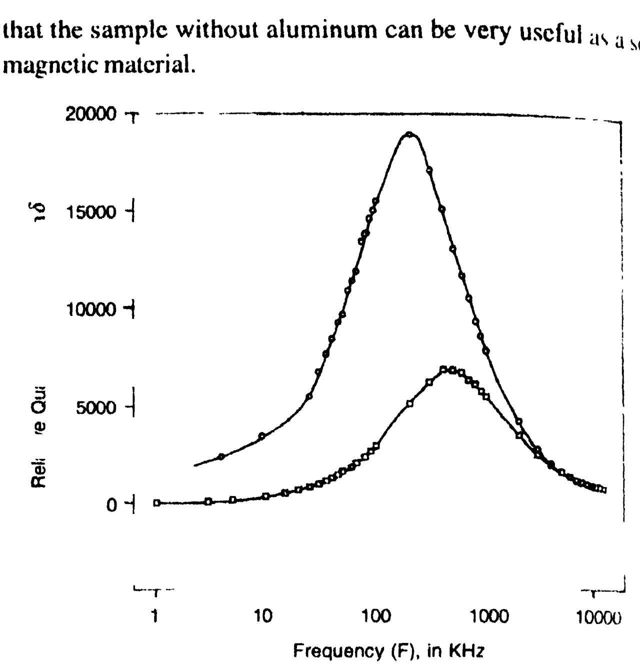

Figure 7. Frequency dependence of the relative quality factor of amorphous ribbons with compositions $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ □- $Fe_{82}Al_3Si_5B_{10}$ and o- $Fe_{82}Si_8B_{10}$.

The specific magnetization (σ_s) as a function of magnetic field (H) is plotted in Figure 8 for both the samples. The value of the specific magnetization is higher in the case of the sample with composition $Fe_{82}Al_3Si_5B_{10}$. Since magnetization as a function of field shown in Figure 8 indicates that the sample with aluminum substitution has higher magnetization permeability of this sample is also expected to be higher when the applied field is sufficiently strong to cause the domain wall motion. This is observed in the magnetization measurements of

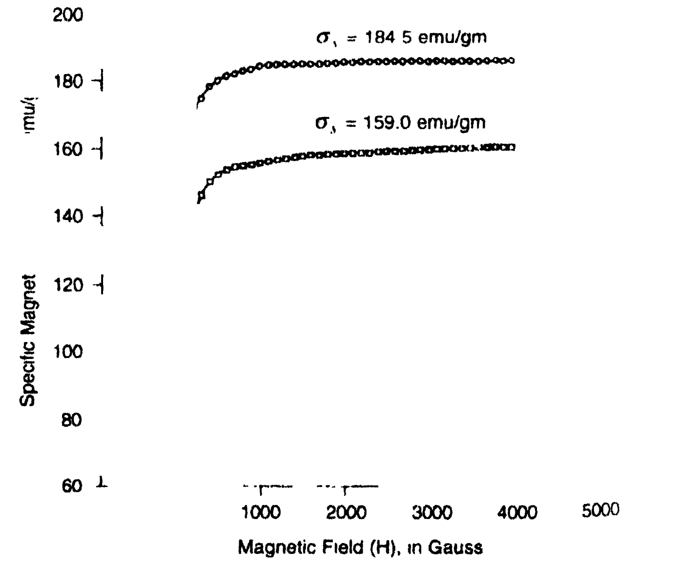

Figure 8. Specific magnetization as a function of magnetic field of amorphous ribbons with compositions $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ o- $Fe_{82}Al_3Si_5B_{10}$ and □- $Fe_{82}Si_8B_{10}$.

both the ribbons. For both the samples, the saturation is reached at very low magnetic field indicating the ribbons as soft magnetic material. The value of the saturation magnetization is estimated from the magnetization curve of Figure 8 as 184.5 emu/gm and 159 emu/gm for $Fe_{82}Al_3Si_5B_{10}$ and $Fe_{82}Si_8B_{10}$ respectively. However, the initial permeability value for aluminum substituted ribbon shows lower values. This is because in our LCR Bridge the applied field was very low of the order of 0.11 A/m, which was insufficient to overcome the local barriers to domain wall movement. This is also expected because aluminum increases magnetostriction, which for strained samples increases coercivity.

4. Conclusions

Iron boron-silicon (Fe-B-Si) amorphous magnetic ribbon shows an interesting magnetic properties as soft magnetic material. Therefore, it can be concluded here that the amorphous magnetic ribbon $Fe_{82}Si_8B_{10}$ can be very useful as core material in the electrical and electronic industries. Aluminum substitution increases both specific magnetization and Curie temperature. However, the permeability of the amorphous magnetic ribbon $Fe_{82}Si_8B_{10}$ is higher than that of $Fe_{82}Al_3Si_5B_{10}$ indicating that ribbons with aluminum substitution have lower initial permeability.

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